

Functional Electrical Stimulation of the Extremities in the Neurological Patient: A Review

The use of functional electrical stimulation (FES) in the treatment of neurological conditions has an extensive history, one that has seen great advances in recent years. Developments in this area of rehabilitation are outlined and avenues for future research and clinical study suggested. The application of FES to the neurological patient may be of considerable benefit alongside conventional facilitatory/inhibitory techniques. The physiotherapist is ideally placed to participate in studies of this modality to determine its role in clinical practice.

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Early attempts to treat muscle paralysis using electricity have an intriguing history spanning over 2000 years (Schechter 1971, McNeal 1973, Geddes 1984). In 1744, Kratzenstein was credited with the use of 'static electricity' to correct contracture of the fingers (Reswick 1973), and by the 19th century, Duchenne had expanded this technique to the stimulation of nerves through surface electrodes placed over nerve trunks and motor points. He also discovered that electrical stimulation could produce relaxation of spastic antagonists (Kaplan 1959). Since the early 1960's a wealth of information has been published highlighting technological advances in FES and the potential for rehabilitation of the neurological patient through neuromotor plasticity. Much of this literature has been reported in bioengineering publications [see Trnkoczy (1978) and Vodovnik *et al* (1981) for comprehensive reviews], therefore the purpose of this paper is to bring recent FES developments to the attention of physiotherapists in the hope of encouraging greater use of FES and critical evaluation of its role within clinical practice.

Contemporary Overview

In the 1950's, Levine *et al* (1952) investigated the use of electrical stimulation to relieve spasticity in hemiplegic patients and noted a transient reduction which was postulated to represent reciprocal inhibition. The term 'functional electrotherapy' was adopted by Liberson *et al* (1961) following their early work using electrical stimulation to improve the gait of hemiplegic patients. The current term, 'Functional Electrical Stimulation', was coined by Moe and Post (1962) to describe the electrical stimulation of muscle deprived of neural control to produce a functionally useful contraction. Today, FES is employed to reduce spasticity, facilitate the return of voluntary movement and as an orthosis to promote function in paretic muscle.

Functional electrical stimulation has been used to improve motor control in patients with hemiplegia (Gracanic 1972, Merletti *et al* 1979), spinal cord injury [SCI] (Bajd *et al* 1983, Cybulski *et al* 1984), multiple sclerosis [MS] (Carnstan *et al* 1977) and cerebral palsy [CP] (Gracanic *et al* 1976) (Examples

of clinical studies are presented in the Table).

Vodovnik *et al* (1981) summarized the clinical objectives of FES as:

1. Support and promotion of spontaneous (neurological) recovery of impaired motor functions of paralyzed extremities and the influence on the development of release phenomenon in the early phase after central nervous system (CNS) damage;
2. Further the development of motor function in children with CP;
3. Restoration of basic reflex motor mechanisms involved in rhythmic activities (*eg* gait) that are integrated mainly at the spinal cord level;
4. Substituting motor functions absent as a result of CNS lesion;
5. Prevention or correction of locomotor dysfunction resulting from insufficient postural control or associated changes in sensorimotor mechanisms integrated at various CNS levels.

The majority of FES investigations have been concerned with gait dysfunction (Kralj and Vodovnik 1977), spasticity (Alferi 1982, Bajd *et al* 1985) and upper limb function (Peckham and

Functional Electrical Stimulation in Neurology

Table: Examples of Studies Used to Evaluate FES for Improving Standing Balance, Gait, Hand Function and to Treat Spasticity

FES Therapy												
	Author [Year]	Sample	Muscle or Nerve	Pulse Shape	Pulse Frequency [Hz]	Pulse Duration [ms]	Surge on/off Ramp [seconds]	Current Intensity	Treatment Period Sessions	Evaluation Objective/Subjective	Results	
SPASTICITY	Alfien 1982	115 CVA	Deltoid Ext W & F Q, DF & P	Sq W	50	0.5	2/2	—	Variable	Daily, 5-15 sessions 10 mins "	Clinical assessment of hypertonus	↓ spasticity (transient) continued to diminish
	Vodovnik <i>et al</i> 1984a	7 SCI	Q & H	M Ph Sq W	30	0.3	Variable Cycle	21	Variable	3 sessions	Pendulum test	Variable ↓ spasticity No ↑ in spasticity 50% SCI may benefit from FES
	Vodovnik <i>et al</i> 1984b	10 CVA	Q & H	M Ph Sq W	30	0.3	5/5	21	Max Tol	1 session 30 mins H, then Alt Q & H	Pendulum test	5 patients ↑ spasticity 3 ↓ spasticity post Q FES
	Bajd <i>et al</i> 1985	6 SCI	Q	M Ph Rect	100	0.3	—	—	Low	1 test session	Pendulum test — repeated 2hrs later	Transient decrease in spasticity
UPPER LIMB	Long & Masciarelli 1963	1 SCI (C4/5)	Extensor Digitorum	—	55	0.2	—	—	Variable	16 mths	Subjective	Improved hand function
	Baker <i>et al</i> 1979	16 CVA	Wrist Finger extensors	Sq W	33	0.2	7 / 10	3 / 0	Max Tol	4 weeks 2/3 day, Rx 15-30mins	Passive ROM Sensation tests Spasticity Extensor strength	↑ Wrist extension ↓ Contractures ↓ Spasticity
	Bowman <i>et al</i> 1979	30 CVA 15 Rx gp 15 FES	Wrist Extensors	Sq W	35	0.2	6-8 / 20	3 / 0	Sub Max	4 weeks 2 sessions/day 30 minutes	MVC wrist torque ROM wrist extension Dynamic, resisted exes	280% ↑ MVC W torque Control gp NS change 200% ↑ in joint range 50% ↑ in control gp ROM
	Hansen 1979	11 CVA	Wrist extensors	M Ph Sq W	100	0.1	2-10 on	Variable	Sub max	—	Hand function EMG control EMG feedback	↑ Wrist extensor torque
	Peckham <i>et al</i> 1980	5 SCI C6 or C7	Wrist & thumb extensors	—	—	—	—	—	Variable	Up to 2 years	Hand function Key grp, release	↑ functional activities ↑ eating and writing
	Kinwinski 1984	1 CVA	Brachioradialis Radial n	—	50	1.0	10/20	—	—	weeks 15 mins 2/day	Hand control spasticity	↑ hand ROM ↑ finger extension ↓ flexor spasticity
	Kroll <i>et al</i> 1986	3 CVA	Biceps & Triceps	Sq W	100	1.0	—	—	Variable	6 weeks 25 sessions 30 mins/session	EMG	50% ↑ in EMG signal Maintained " 40 days
LOWER LIMB	Liberson <i>et al</i> 1961	7 CVA	P & DF	—	30	0.02	—	—	—	—	Gait evaluation	Improved gait with FES Transitory carry-over
	Carnstam <i>et al</i> 1977	7 CVA/MS	P & DF	—	30	0.5	300ms / 1s	—	Sub Max	Variable (several years)	Achilles reflex Gait assessment DF force/EMG	Variable ↑ DF force/EMG ↓ S1 reflex excitability FES ↓ motor excitability in antagonists i.e. plantar flexors
	Merletti <i>et al</i> 1978	49 CVA 24 PT 24 PT & FES	P & DF	M Ph Rect	30	0.3	15/3	—	Variable	5 weeks, 6 days/wk 20 mins/session plus 1 hr PT/day	MVC ankle DF	x3 ↑ DF force (FES group) [Significant <i>p</i> < 0.02]
	Stanic <i>et al</i> 1978	11 CVA	P & DF	Rect	30-40	0.15-0.3	—	—	Variable	1 month 3 sessions/wk	Gait evaluation	Greater correction during swing phase
	Bajd <i>et al</i> 1983	12 SCI	Q, Sural n Saphenous n Peroneal n	M P Rect	20	0.3	—	—	Variable	1-3 months	Rise to stand Stand without aid Ambulate with frame	Variable response
	Gruner <i>et al</i> 1983	6 SCI	Q	—	30	0.2	Reciprocal limbs	—	Variable	30 sessions 9 weeks 3 sessions/wk 2 x 10 min session	Cardiac function Q strength	HR was not elevated ↑ Sys BP 20 mmhg + load Strength & endurance ↑
	Marsolais <i>et al</i> 1983	3 CVA	Q, H E H Abd	—	50	0.1	Temporal sequence for gait	—	Variable	Variable 8 mths — 1 year	Cyber test for Q strength, 60°/s static 0°/s	↑ increase in strength ↑ gait, " 30 mins unaided ↓ spasticity
	Winchester <i>et al</i> 1983	40 CVA 20 Expt gp 20 controls	Q	A B P Sq W	30	0.22	2 s ↑	Variable	Variable	5 days/4 wk PT x 4 day all pts 2 hrs/day FES 30 mins PF/day	Pass/act knee ROM Static Q strength Thigh girth	Rx gp ↑ knee torque NS change in Q spasticity
Braun <i>et al</i> 1985	4 SCI	Q, H E F reflex	Rect	24	0.3	—	—	Variable	22 weeks 10-30 days 10-30 mins/x2 day Supported standing Reciprocal gait	Gait evaluation Force platform	↑ mobility during gait ↓ stride and stance times	

KEY TO MUSCLE GROUP

Ex W&F Extensors Wrist & Fingers
H E Hip extensors
H Abd Hip Abductors
Q Quadriceps
H Hamstrings
P Peroneals
DF Dorsiflexors
F reflex Flexion reflex

KEY TO PATIENT SAMPLE

CVA Cerebro Vascular Accident
SCI Spinal Cord Injury
MS Multiple Sclerosis

KEY TO SYMBOLS

NS Non Significant
↓ Decrease
↑ Increase
MVC Maximal voluntary contraction

KEY TO PULSE SHAPE

M Ph Monophasic
Rect Rectangular
Sq W Square Wave
A Asymmetrical

Mortimer 1977, Baker *et al* 1979). Hypoventilation problems associated with high level SCI patients have been managed successfully with diaphragm pacing using phrenic nerve stimulation (Glenn *et al* 1977). In addition, FES has been used to improve bladder disturbance (Tallis *et al* 1983), and in the management of idiopathic scoliosis, reduction in the extent of spinal curvature has been achieved with some patients (Axelgaard 1984). Developments in electro-motor stimulation for musculoskeletal conditions is another area that has received recent attention (Lloyd *et al* 1986).

Neurophysiological mechanisms behind improvements in motor function following FES have been advanced and the models developed by Dimitrijevic *et al* (1968), Gracanic (1978) and Vodovnik (1981a) are presented. In addition, details of clinical studies using FES in the neurological patient and avenues for further investigation will be outlined.

Functional Electrical Stimulation as an Orthotic Substitution

The original application of FES was as an orthotic substitute for absent muscle function. Baker (1981) outlined the major orthotic applications for FES as: provision of adequate dorsiflexion in patients with foot-drop unresponsive to muscle re-education, maintenance of gleno-humeral alignment in the paretic shoulder, provision of hip and knee extension to allow stance and reciprocal gait in the SCI patient and as an external control of hand opening and prehension in high level quadriplegic patients. In the future greater emphasis may be placed on the therapeutic potential of FES, as the recent study by Valencic *et al* (1986) confirms the prospect of improving motor function even in patients with denervated muscle.

The Therapeutic Role of Functional Electrical Stimulation

The transient improvement of dorsiflexion described by Liberson *et al* (1961) following FES to the peroneal

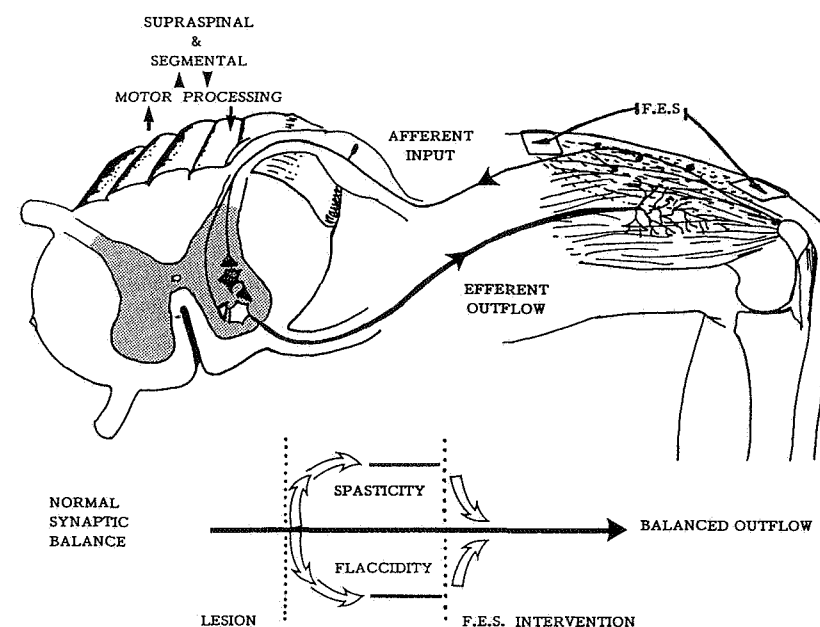


Figure: Schematic representation of FES, depicting the restoration of a functional 'synaptic' balance within the motoneurone pool attributed to the sensori-motor stimulation. This model proposes the selective facilitation of hypotonic states and inhibition of spasticity through the augmentation of intact interneuronal and supra-segmental influences (modified from Vodovnik 1981a).

nerve to correct hemiplegic foot-drop, prompted a re-evaluation of this treatment. This phenomenon was termed 'carry-over' by McNeal (1973). In a later study by Dimitrijevic and Gracanic (1968), hemiplegic gait was studied using electromyography (EMG) recorded from the lower limbs before and after FES. This revealed that more normal phasic motor behaviour was induced with less gross motor synergies. Takebe and Basmajian (1976) also employed EMG analysis of gait to contrast the efficacy of FES and biofeedback, and suggested that both may improve voluntary motor control through a similar mechanism. Gracanic (1978) examined 'carry-over' following FES for gait and upper limb dysfunction and concluded that FES may be more successful in improving gait as it is a rhythmic activity controlled largely at the spinal level, while neuromotor coordination of the upper limb typically requires supra-spinal control. Waters (1984) stated that even though a test-

able conceptual model is lacking and the neural pathways involved remain obscure, 'carry-over' can be used to supplement biofeedback training for increasing motor control.

The duration of post-treatment improvement is variable, some writers reporting transient effects (Liberson *et al* 1961, Stanic *et al* 1978), while others describe sustained benefit (Gracanic 1972, Vodovnik and Reserbek 1973, Stefancic *et al* 1976). Carry-over effects also appear to be specific to the region stimulated, as Andrews *et al* (1985) reported no improvement in quadriceps spasticity in SCI patients, when cutaneously stimulating L1-2 and S1-2 dermatomes, yet described marked reduction in spasticity when FES was applied to the L3-4 distribution.

Neurophysiological Model for Functional Electrical Stimulation

The early conceptual model of FES developed by Dimitrijevic *et al* (1968), Gracanic (1972), and more recently

Vodovnik (1981a), proposes that the programmed stimulation achieves facilitation of the spinal motor neurone pool through the afferent input to the cord and suppression of inhibitory interneuron influences, resulting in a lasting functional motor improvement (Figure).

Vodovnik (1981a) suggested that 'synaptic' imbalance between excitatory and inhibitory influences mediating over motor outflow and reflex activity at the segmental level, results in either flaccidity or spasticity. Functional electrical stimulation may therefore provide a patterned motor activation through the simultaneous stimulation of sensory receptors. Although the precise role of long-loop conducting reflexes [eg spino-bulbo-spinal reflex pathway, Shimamura and Livingstone (1963)] in man is not clearly understood (Meier-Ewert *et al* 1972), there is some suggestion that this system may be responsible for functional improvements in the motor responses of neurological patients (Vodovnik 1981b). Even where supraspinal control is absent or impaired, as in the SCI patient, the propriospinal interneuronal system is capable of integrating afferent input to provide co-ordination of movement and postural adjustment (Dimitrijevic and Dimitrijevic 1983). Vodovnik (1981b) proposed that the nervous system filters FES input to facilitate the hypotonic state and inhibit the hypertonic. Kroll *et al* (1986) confirmed the potential for improvement in voluntary motor activity following a specific pattern of stimulation to the affected upper limb. The stimulation parameters were based on voluntary activation patterns of the biceps and triceps recorded from the unaffected limb using EMG. Lasting improvements in arm function, still detectable over one month after the FES programme, were achieved with three hemiplegic patients previously considered to be incapable of further recovery. This approach using EMG modelling of normal motor responses may

provide an important step towards optimizing clinical FES protocols.

Stimulus Parameters

Stimulus characteristics suited to achieving functional stimulation, without problems of fatigue and electrode/tissue reactions, have been refined since the early reports by Crago *et al* (1974) and Peckham *et al* (1976). These considerations have been extensively studied by Solomonow (1984) who noted a reduction in onset of fatigue with a protocol that involved asynchronous stimulation pulse trains. This approach has been adopted for improving hand control in quadriplegic patients.

Smoothing of the muscle contraction can be achieved with a stimulation frequency between 20 and 35 pulses per second. Benton *et al* (1981) suggest that high frequencies may not achieve greater force and are more likely to produce muscle fatigue due to the increased rate of motor unit recruitment. Sustained activation of motor units achieved during an electrically stimulated contraction often results in a greater energy expenditure than that required to produce the same physiologic muscle contraction (Baker 1981). This may be due to the asynchronous nature of motor unit recruitment usually seen in sub-maximal voluntary contractions. The problem of fatigue has been identified as a major limitation in FES programmes for paraplegic patients using a standing orthosis (Kralj *et al* 1980, Cybulski *et al* 1984).

The pulse duration (width) of 0.2-0.3ms, commonly adopted by investigators (Grant and Swain 1985) is sufficient to generate a contraction with a moderate current intensity. Shorter pulse durations tend to require greater intensities, while longer stimulation pulses may prove less comfortable for the patient (Baker 1981, Alon *et al* 1983).

An important consideration for FES in the neurological patient is the period of time over which the current reaches

maximum intensity. A graded rise time, producing a smooth muscle contraction, is particularly advantageous in treating patients with spasticity. A slow rise time will result in a prolonged stretch of spastic antagonist muscles and facilitate reciprocal inhibition (Baker 1981).

Clinical Applications of Functional Electrical Stimulation to the Extremities

Gait Studies

Gait problems in the hemiplegic patient are often characterized by an inability to dorsiflex the foot during the swing phase; therapy for this deficit has been extensively studied (Dimitrijevic *et al* 1981). One of the earliest FES studies investigated the effects of stimulating the peroneal nerve in subjects with foot drop and prominent inversion of the foot (Liberson *et al* 1961). Stimulation during swing phase appeared to improve gait in all patients and a transitory improvement in voluntary dorsiflexion after the period of stimulation was observed.

In 1968, Dimitrijevic and colleagues presented results of a 'functional electronic peroneal brace' (referred to as the Ljubljana FEPB) and reported a considerable improvement in the gait of 10 patients who were able to walk more safely and for longer periods.

In an extensive study of the Ljubljana FEPB for stimulation of dorsiflexors during gait, Gracanin (1972) concluded that it might have a useful role in approximately 30 per cent of the hemiplegic population. Those patients who were independently ambulant without other major gait abnormalities were considered most suitable. Reasons for the lack of FES suitability in the remaining 70 per cent of patients were not discussed.

Carnstam *et al* (1977) studied EMG recordings, maximal isometric torques (pre and post stimulation), tendo-achilles and patellar reflexes (and EMG

during gait with one patient) in seven patients with hemiparesis or spastic paraparesis resulting from MS. A significant increase in maximal voluntary torque was recorded. Improvements in post-stimulation values were reported to be inversely related to pre-stimulation strength. They observed that strength increases in the dorsiflexor group possibly represented a decreased resistance by the spastic plantarflexors.

The effect of chronic electrical stimulation on nerve conduction velocity was investigated by Waters *et al* (1975) in a study involving nine hemiplegic patients with implanted peroneal electrodes (present for a mean duration of 24 months). No significant change in nerve conduction velocity was recorded. While eight of the nine patients demonstrated progressive improvement in maximal voluntary dorsiflexor force, other functional parameters were not reported.

A multi-channel stimulator was developed by Stanic *et al* (1978) for gait studies. The authors outlined an extensive list of prerequisites for FES and criteria for patient selection. An improved gait was achieved in eleven hemiplegic patients treated over a three month period according to clinical assessment. However the stimulation sequences were pre-programmed and consequently did not permit exact synchronization with the phases of gait. Moreover, surface electrode/tissue coupling was identified as a problem along with discomfort and fatigue during higher intensity stimulation.

A transient increase in muscle force following daily FES to dorsiflexors/evertors of the ankle was observed by Merletti and co-workers (1978). Two patient groups received conventional physiotherapy with one also receiving FES. Maximal dorsiflexor torques were found to be approximately three times greater in the stimulated group. In a further study, Merletti *et al* (1979) evaluated clinical results from peroneal nerve stimulation in 50 hemiparetic patients. Criteria for patient selection in-

cluded: absence of major communication deficits or emotional disturbances, little or no sensory loss, full range of passive movement of all joints in the affected lower limb, and the ability to walk independently. Patient response was graded according to gains in voluntary movement and reduction of spasticity. Gait correction was achieved in 76 per cent of cases (orthotic role), while a lasting improvement in lower limb function was noted in 34 per cent of patients. Those with a shorter elapsed time since their lesion and less spasticity demonstrated greater progress.

In 1976, Gracanin and co-workers reported a modification of the FEPB which was evaluated with 120 CP children (aged one year and over) for unilateral or bilateral peroneal nerve stimulation. An improved gait was achieved in most patients and the term 'contralaterally controlled alternate functional electrical stimulation' (CCA FES) was coined to describe the adapted peroneal brace. The brace was contraindicated in those children with severe valgus deformity of the ankle or insufficient extensor tone to allow them to stand once spasticity was inhibited. Difficulties were experienced in initiating stimulation via a heel switch as many of these children did not have heel strike prior to the stimulation programme. Vodovnik *et al* (1981) described the successful application of CCA FES in 263 out of 415 children with CP. One third exhibited improvement in gait following FES which was maintained after the stimulation programme was discontinued.

Some attention has been directed towards achieving a standing posture and basic locomotion in patients with paraplegia as a result of spinal cord injuries. Kantowitz (1963) briefly described the use of FES for achieving a standing posture in a T7 paraplegic through the simultaneous application of FES to the hip and knee extensors. Vodovnik *et al* (1981) noted that the few studies reported to date, have dealt

with relatively small numbers of patients and have achieved limited functional results. Patients with incomplete spinal cord lesions may be more suited to FES as there is greater potential for a therapeutic effect. However, much work is being conducted in many centres in an attempt to define the role of FES in restoring upper limb function and in some cases facilitating locomotion.

Bajd *et al* (1983) describe a programme of assisted ambulation involving twelve paraplegic patients with incomplete spinal cord lesions below T5. Patients initially underwent a training programme involving up to three hours/day stimulation to strengthen atrophied quadriceps. All patients were able to rise from the sitting position with arm support and stand for up to twenty minutes with stimulation to hip and knee extensors. A four channel stimulator was used to provide a reciprocal gait sequence in four patients. Swing phase was initiated by stimulation of the saphenous nerve to elicit the preserved flexor withdrawal reflex. Only one patient achieved functional gait which permitted ambulation outdoors with the aid of crutches and standby assistance. Other patients participating in the programme report improved bowel and bladder control, reduction in spasticity and a decrease in the incidence of pressure areas. Braun and co-workers (1985) reported standing times of 15-20 minutes in four paraplegic patients with complete lesions below the level of T5. Two of the four patients were able to ambulate with either a walker or elbow crutches. No comment was made regarding patient stability or the need for standby assistance, a factor that would be important for relative functional independence. Other benefits noted were the reduction of adductor spasticity and dependent oedema of the lower limbs, and increased strength of the abdominal muscles. Isakov *et al* (1985) evaluated the energy cost of FES during standing and gait and while noting that

standing could be maintained without difficulty, found that FES-assisted ambulation had an energy cost almost ten times that of normal gait, rendering it inefficient and exhaustive. Perhaps the greatest achievement for paraplegic patients has been the ability to stand and transfer more independently (Grenfell 1985).

The most comprehensive studies to date, particularly in relation to motor control in SCI patients, have been documented by Dimitrijevic and co-workers from the Texas Institute for Rehabilitation and Research. In a series of experiments involving 38 SCI patients (Dimitrijevic *et al* 1984), motor retraining potential was determined by studying stretch reflex behaviour to vibration, pendulum testing, the elicitation of clonus, tendon taps and response to noxious stimuli. Presence of long tract conducting systems were apparent in EMG recordings even in some 'clinically' complete cord injured patients. These findings provide further incentive for FES programmes to investigate the possible restoration of motor function in this patient group.

Upper Limb Functional Electrical Stimulation

While Long and Masciarelli (1963) described a splint designed to maximize hand function in a high level quadriplegic, relatively few applications of FES to improve upper limb function in other patient groups have been reported. Most efforts have been to correct very specific deficits, for example to produce wrist and finger extension via radial nerve stimulation in patients who have basic control of wrist and finger flexion (Gracanin 1972, Rebersek and Vodovnik 1973, Merletti *et al* 1975). In 1968, Dimitrijevic and colleagues described a modification of Long and Masciarelli's 'electrophysiological splint', which stimulated the median, ulnar and radial nerves to achieve functional movement in hemiplegic patients. Rebersek and Vodovnik (1973) suggested that stimulation

controls were often inadequate to produce sufficiently intricate hand movements and that there was limited motor selectivity from surface electrodes. They described an orthotic device which utilized a position control operated by the unaffected shoulder in patients with preserved finger flexion but lacking extension. Hand opening occurred in proportion to the amount of elevation of the unaffected shoulder, which provided a degree of fine control. Patients were able to perform timed manipulative tasks after a short period of training that were unable to be performed previously. The authors concluded that proportionally controlled devices clearly demonstrated advantages over those with a sequenced control.

Merletti *et al* (1975) reported the use of a dual channel stimulator, providing elbow extension by elevation of the unaffected shoulder and extension of the wrist and fingers induced by shoulder protraction. Five hemiplegic patients performed a task involving moving objects from one clearly defined point to another. This task required minimal training and three of the five exhibited improved voluntary control of elbow extension. Patients could not perform hand opening without stimulation.

The problem of more exacting stimulation control was addressed by Hansen (1979), who described an FES system which used an EMG signal as a monitor. This allowed stimulation of the wrist extensors controlled by the patient's EMG output. Even severely paretic muscles were capable of producing an efficient EMG signal which led to improved wrist extension control and power.

Bowman and co-workers (1979) combined electrical stimulation with positional feedback from EMG to improve extension in the hemiplegic wrist. A control group received conventional therapy, while the experimental group received 'positional feedback stimulation training' (PFST) for 30 minutes,

twice daily. The apparatus allowed the maximum range of voluntary wrist extension before delivering the stimulation to complete the range of joint motion. At the end of the four week programme patients in the stimulation group showed greater isometric wrist extension torques compared to the controls.

Peckham and co-workers (1980) and Peckham (1983) described an FES orthosis which improved grasp in C5-6 quadriplegics. Palmar grasp was provided by stimulation of the finger flexor and thumb abductor muscles, while lateral prehension (between thumb and lateral side of the index finger, as in grasping a key) allowed reasonably fine manipulation of small objects. Additional external splintage of wrist extension was necessary in C5 quadriplegics. Control signals were supplied by changes in head or shoulder position or from EMG activity generated during voluntary contraction of a muscle that retained normal function. In some cases the stimulation electrodes were implanted in the forearm for long term use. Kiwerski (1984) reported the use of implanted radial nerve electrodes in one hemiplegic patient with spasticity affecting hand function. He attributed strengthening of finger and wrist extensors to the improved function and decreased spasticity.

Kroll *et al* (1986) took a different approach to the provision of an appropriate stimulation programme, devising an FES input to the involved limb based on individual EMG recordings from the unaffected upper limbs of three flaccid hemiplegic patients. A pre-test session to monitor bilateral biceps and triceps muscle activity was followed by 25 sessions of FES to the affected limb. An FES programme was established from the temporal sequence of agonist and antagonist firing patterns and on the ratios of flexor to extensor EMG intensity and duration, recorded from the unaffected arm. During the course of treatment all subjects recovered full movement of the

thumb and partial movement of the fingers, wrist, elbow and shoulder. EMG recordings from the paretic limb increased to 50 per cent of the output of the unaffected limb, however normal firing patterns were not completely restored. Improvements were found to have been maintained on re-testing 40 days after cessation of the stimulation programme. Kroll argued that these results strongly support the model of Vodovnik (1981a) (see Figure) who described a direct motor response resulting from stimulation of the affected muscles and a longer-lasting, indirect restoration of motoneurone balance due to the sensory stimulation.

Functional Electrical Stimulation and Spasticity

A number of authors (Levine *et al* 1952, Baker *et al* 1979, Alfieri 1982, Vodovnik *et al* 1984a, 1984b) have described the use of electrical stimulation to decrease spasticity. Levine *et al* (1952) documented four cases of patients with spasticity resulting from hemiplegia, incomplete spinal cord lesion and multiple sclerosis. Functional electrical stimulation applied to antagonists resulted in inhibition of spasticity and in one case, improved voluntary function. Baker *et al* (1979) applied daily FES to wrist extensors of sixteen hemiplegic patients with spasticity of the wrist flexors. Significant improvement in passive range of wrist extension was noted in all patients and over half demonstrated an increase in voluntary wrist extension torque. At two months post-stimulation, a decline in passive wrist joint range was noted despite regular self-range of motion exercises.

In a further study involving 115 hemiplegic patients, Alfieri (1982) applied FES to antagonists of the spastic muscle groups (*ie*, patients with spasticity of their plantarflexors, quadriceps, wrist and finger flexors). Spasticity was noted to reappear approximately one hour after treatment but diminished in intensity after approximately ten treat-

ments. Alfieri advocated that the electrical stimulus must be applied to the 'weak' muscle group taking care to avoid overflow into the spastic muscle(s). However this contention was not confirmed by Vodovnik and co-workers (1984a, 1984b) who investigated the effects of electrical stimulation on quadriceps hypertonus in seven SCI and ten hemiparetic patients. Stimulation of the spastic muscles was compared with stimulation of the antagonists. Of these, five spinal injured and eight hemiplegic patients showed reduction in spasticity following two treatment sessions of 30 minutes duration. No conclusions were able to be drawn as to whether antagonist or spastic muscle stimulation was more efficacious, however, none of the patients experienced increased spasticity. One hemiplegic patient who maintained the programme of hamstring stimulation for one month, exhibited reduction of quadriceps spasticity sufficient to cancel surgery planned to release her m. rectus femoris. In addition, other studies have suggested that increased active range of movement following FES may, in part, be attributed to decreased spasticity in antagonist muscle groups (Carnstam *et al* 1977).

Afferent Functional Electrical Stimulation

Dimitrijevic *et al* (1968), described the use of external 'afferent' stimulation (FES) to improve proprioceptive feedback and facilitate a functional motor response. They provided an example of afferent stimulation (*ie* insufficient to produce stimulation of motor nerves) to the paralysed wrist extensors of a hemiplegic patient. Prior to the stimulation, the patient was unable to perform volitional wrist extension. No EMG activity of the extensor muscles was recorded during afferent stimulation, however following this the patient was able to produce some active wrist extension. This finding was confirmed by Vodovnik and Rebersek (1973) who performed a similar ex-

periment on three hemiplegic patients who lacked voluntary control of dorsiflexion. After afferent FES, the EMG signal recorded from dorsiflexors was much greater than the EMG recorded from stimulation alone or the pre-stimulation EMG during volitional effort.

Bajd *et al* (1985) described the use of low intensity afferent stimulation to the L3-4 dermatome in six SCI patients with quadriceps spasticity. Half the patients achieved substantial reduction in spasticity which persisted for up to two hours. In a further study, Andrews *et al* (1985), evaluated quadriceps spasticity following afferent stimulation of the L1-2, L3-4, and S1-2 dermatomes. Reduction in spasticity lasting for ninety minutes was specific to the stimulation to L3-4. Identical stimulation protocols to the two adjacent dermatome levels produced no change in spasticity.

Discussion

Functional electrical stimulation is a rapidly developing area in the rehabilitation of patients with neuromotor disorders. The application of FES to the upper limb has not achieved the same success as stimulation of the lower extremity. This situation may be remedied as more sophisticated stimulation systems become available, incorporating more flexible controls and utilizing sensory feedback to the user (Thrope *et al* 1985, Crago *et al* 1986). Developments in multi-channel FES systems for gait control will depend on refinements in modelling normal locomotion and the miniaturization of such systems for independent use by patients. Further research is presently being directed towards improving intramuscular stimulation (Peckham 1983) and refining surface stimulation techniques. Apart from general descriptions of FES for treating various neuromotor disorders (Benton *et al* 1981) few exacting clinical regimes have been proposed.

The majority of early FES studies used clinical assessments rather than scientific trials to consider the efficacy of FES. Recent investigations have adopted more objective criteria, for example, with the use of EMG (Kroll *et al* 1986), force plate measurement during gait and postural assessment (van Griethuysen *et al* 1982), computer analysis of gait patterns (Braun *et al* 1985), pendulum testing for measuring spasticity (Bajd and Vodovnik 1984), reflex excitability changes (Carnstram *et al* 1977), muscle strength, endurance and cardiac function after FES (Gruner *et al* 1983, Phillips *et al* 1984) (see Table).

Controlling for patient variability is a feature that few investigators have incorporated into FES research. The studies by Merletti *et al* (1978) and Bowman *et al* (1979) noted significant improvements between treatment and control groups on such parameters as strength and joint range. However while Winchester *et al* (1983) observed a similar improvement in quadriceps strength of the FES group, no change in spasticity was recorded. Despite difficulties with patient selection, greater consideration of experimental controls is necessary if clear guidelines for using FES are to develop. Few writers document attempts to assess the reliability of test measures through adequate repeated pre-testing. Validating these procedures is especially important in the neurological patient when considering the unpredictable nature of unmodulated reflexes, tissue fatigue (nerve and muscle), and force changes in one muscle group influencing adjacent limb segments (Trnkoczy 1978). Despite these limitations, attempts at modelling FES requirements for normal limb function continue. The difficulties in providing a flexible FES system modulated by the patient's intact feedback control (closed-loop) is currently the focus of much attention (Cybeski 1984, Solomonow *et al* 1984, Thrope *et al* 1985, Crago *et al* 1986).

An overview of literature has been presented outlining some of the studies

that have investigated the use of FES relating to upper and lower extremity dysfunction in the neurological patient. Although it would appear that hemiplegics are most likely to benefit from FES (Vodovnik *et al* 1977), applications to other neurological disorders such as multiple sclerosis, cerebral palsy or spinal cord injury have been investigated. The three main areas described have been correction of gait anomalies, improvement of upper limb function and reduction of spasticity. The efficacy of FES has been related to the improved voluntary motor control exhibited by many patients following treatment. The neurophysiological model proposed suggests that FES provides a selective, programmed input to either paretic or spastic condition, which activates intact segmental and intersegmental motor pathways, restoring more normal neuromotor function.

Present research findings have proposed the clinical efficacy of utilizing FES to improve the voluntary control of neurologically impaired motor systems. A precise understanding of the mechanisms involved remains for future investigations. However the model presented by Vodovnik (1981a) and others suggests the importance of sensory pathways subserving segmental and higher centres involved in motor processing. These investigations suggest that FES is a useful addition to conventional facilitatory and inhibitory techniques in the management of the neurological patient. Future studies will need to provide more exacting clinical protocols aligned with specific neurological disorders, particularly in relation to problems of spasticity. The physiotherapist is ideally placed to contribute to this developing field of clinical study.

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